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Integrating Triple Bottom Line in Sustainable Chemical Supplier Selection: A Compromise Decision-Making-Based Spherical Fuzzy Approach

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Abstract: As a consequence of increased awareness of environmental preservation and the associated rigorous regulations, the adoption of sustainable practices has become a crucial element for corporate organizations in regard to their supply chains. In the chemical industry, which is characterized by high risks, high pollution, and high efficiency, these characteristics can help businesses analyze their long-term development and sustainability. The goal of this research is to analyze and choose possible suppliers based on their sustainability performance in the chemical sector. A methodology based on multi-criteria decision making (MCDM) is proposed for this evaluation, using spherical fuzzy analytical hierarchy process (SF-AHP) and combined compromise solution (CoCoSo) methods, in which the novel spherical fuzzy sets theory is employed to present the ambiguous linguistic preferences of experts. In the first stage, an evaluation criteria system is identified through literature review and experts' opinions. The SF-AHP is used to determine the criteria weights, while the CoCoSo method is utilized to select the right sustainable supplier. A case study in the chemical industry in Vietnam is presented to demonstrate the effectiveness of the proposed approach. From the SF-AHP findings, "equipment system and technology capability", "flexibility and reliability", "logistics cost", "green materials and technologies", and "on-time delivery" were ranked as the five most important criteria. From the CoCoSo analysis, Vietnam National Chemical Group (CHE-05) was found to be the best supplier. A sensitivity study and a comparison analysis of methods were also conducted to verify the robustness of the proposed model, and the priority rankings of the best suppliers were very similar. To the best of our knowledge, this is the first study that has proposed SF-AHP and CoCoSo to prioritize SSS evaluation criteria and determine the best alternatives. The suggested method and findings can be used to make well-informed decisions that help businesses to achieve supply chain sustainability, capture opportunities, and maintain competitiveness through reconfiguring resources. The method could be useful for case studies in other countries and for other sustainability problems.

Keywords: supplier selection; chemical industry; decision-making; SF-AHP; CoCoSo; compromise solution; triple bottom line

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1. Introduction

The industrial revolution 4.0 has opened up many new opportunities for the chemical industry to transform, increasing productivity and quality when applying new science and technology, and promoting green and sustainable growth. In Vietnam, the implementation of the country's Doi Moi policy and economic reforms have boosted economic growth and industrial–agricultural development. The demand for chemical raw materials is increasing, with an annual growth rate for chemical production of 15% [1]. The total annual output of Vietnam's chemical industry accounts for about 10–11% of the entire industrial GDP. As of 2020, the whole chemical industry has about 1818 manufacturing enterprises distributed across six regions in the country [2]. Currently, they have about 2.7 million employees, of which 725,000 are directly involved in producing chemicals and chemical products.

The increasing demand for chemicals in the market has led to the strong growth of chemical companies in recent years [3]. Chemical companies must also respond more quickly to competition in the context of an increasingly fierce global market. The race among companies with respect to cost, quality, and market share is becoming more urgent. Good input suppliers greatly influence business performance [4]. Therefore, incorporating the three pillars of sustainability, i.e., economic, social, and environmental aspects to ensure sustainable development has been an important strategic task for business organizations in recent years. Suppliers play a vital strategic role in achieving these gains. From an economic perspective, the increase in demand for chemicals is accompanied by higher requirements for quality from chemical suppliers. Cost is a prominent factor that can influence buyer demand. However, for chemical products, it is necessary to estimate the cost of the product along with the cost of shipping and delivery. A good price is an indispensable requirement; therefore, buyers only choose chemical suppliers who offer reasonable prices while ensuring high quality. Not all suppliers can meet this criterion at present. Door-to-door delivery is the deciding factor for buyers. Manufacturers who do not have specialized vehicles to transport chemicals are at a disadvantage because they have to hire an external transport unit. This leads to higher shipping costs, and problems arising during delivery may not be handled in a timely manner. Therefore, it is advisable to choose chemical suppliers with specialized vehicles for transporting chemicals. Regarding social aspects, the partnership between customers and suppliers is also important. Companies will often buy chemicals from close, long-term suppliers, with whom they have good relationships. Therefore, reputation is an essential factor. For example, a reputable and professional enterprise always ensures that the employees' working environment complies with health and safety standards. A safe work environment is important for attracting buyers and improving a company's productivity and product quality [5].

The chemical industry is distinctive in its negative impact on the environment and public health. In addition to customer requirements, reliable chemical suppliers must also meet all quality standards set by the Vietnamese government, especially with regard to environmental friendliness. Indeed, the standards in the chemical industry are constantly changing as they are influenced by various factors such as governmental policies. The government ensures that chemical suppliers and manufacturers comply with its policies on labeling, distribution, and packaging, and these requirements are becoming more and more stringent, in order to reassure consumers. Notably, the government has gradually tightened the environmental conservation regulations in recent years [4]. Reputable chemical manufacturers must comply with environmental protection laws and production standards to minimize the environmental impact of industrial chemical production. In addition to the rules and regulations, these companies are also required to have strict internal policies, to enable the provision of an optimal service and high-quality products.

The above discussion shows that green and sustainable supplier selection (SSS) represents a key decision in the chemical industry's supply chains. A plethora of evaluation criteria are responsible for the feasible and sustainable implementation of chemical supplier selection, from the perspective of a developing country such as Vietnam, including not only the quality of chemicals/services, price, and technology but also many other social and environmental aspects. In this paper, we propose a hybrid multi-criteria decision making (MCDM) approach for SSS based on three pillars of sustainability in the chemical industry, or the so-called triple bottom line (TBL) dimensions, with distinctive economic, environmental, and social characteristics [6–9]. Initially, the evaluation criteria system is identified through a literature review and experts' opinions. Secondly, the analytical hierarchy process method with the novel spherical fuzzy theory (SF-AHP) is employed to analyze and evaluate the criteria, where the spherical fuzzy sets theory is applied in order to deal with uncertainty in this decision-making environment. Finally, the combined compromise solution (CoCoSo) method is employed to determine the right sustainable supplier. Using the proposed integrated MCDM model, a case study involving selecting the best suppliers that have most efficiently employed sustainable practices in their procedures in the chemical industry in Vietnam is presented, to demonstrate the model's effectiveness. In addition, a sensitivity analysis is performed to observe the stability of the results.

This paper contributes to the literature by studying the SSS problem in the context of the Vietnamese chemical industry. This is the first attempt to propose an integrated SF-AHP and CoCoSo approach to identify and prioritize the SSS evaluation criteria and to select the most efficient supplier from a set of alternatives, for sustainability in the supply chain. Both methods are novel techniques that have proved to be effective in various studies in recent times, in applications such as renewable energy [10], location selection [11–13], technology selection [14], supplier selection [15–18], and management issues [19–22]. In the present research, the proposed approach is employed in a real case study, to evaluate the performance of five suppliers in terms of achieving social sustainability goals with the aid of experts' inputs. With regard to managerial implications, our proposed approach and results form a basis for making informed decisions that could help firms to achieve supply chain sustainability, to capture opportunities, and to maintain competitiveness through reconfiguring resources. The method may be useful for case studies in other countries and other sustainability problems.

The remainder of the paper is structured as follows. Section 2 contains a review of the literature on SSS and related criteria. Section 3 discusses the methodology used to conduct the case study described in this paper. Section 4 discusses case illustrations. Section 5 includes a model validation process, to test the effectiveness of the suggested model. Section 6 further discusses the managerial consequences of the proposed model. Section 7 includes concluding remarks and recommendations for further study.

2. Literature Review

2.1. Identification of TBL Criteria for Sustainable Supplier Selection

The TBL criteria for sustainable supplier selection (SSS) were determined in the present study based on a comprehensive literature review and input from professionals in the Vietnamese chemical sector. The literature review entailed searching the keywords, abstracts, and titles of journal contributions through Scopus—the world's largest database, using the terms "sustainable supplier selection", "manufacturing", "chemical industry", "emerging economy", "triple-bottom-line", "criteria", and "supply chain". Using questionnaires, experts in the Vietnamese chemical sector were interviewed to determine whether the identified TBL criteria were "applicable" or "not applicable" to SSS in the Vietnamese chemical industry. After discussion, fifteen TBL criteria were considered to apply to SSS in a Vietnamese chemical sector case study, as shown in Table 1. As indicated in Table 1, the assessment criteria for sustainable supplier selection were classified into economic, environmental, and social dimensions.

Table 1. Literature review summary of SSS evaluation criteria.

Dimension	Criteria	References	Type of Criteria
Economic (EC)	EC1. Quality of chemicals	[7,23–32]	Benefit
	EC2. Price	[23–26,30,31]	Cost
	EC3. Logistics cost	[9,24,33,34]	Cost
	EC4. On-time delivery	[23,25,26,28,30–32]	Benefit
	EC5. Equipment system and technology capability	[26,29,35,36]	Benefit

Table 1. *Cont.*

Dimension	Criteria	References	Type of Criteria
	EC6. Innovativeness	[25,30–32]	Benefit
	EC7. Flexibility and reliability	[25,32,37–40]	Benefit
Social (SO)	SO1. Work safety and labor health	[7,23,25,26,32,35]	Benefit
	SO2. Reputation	[7,25,32,37]	Benefit
	SO3. Disciplinary and security practices	[25,28,32]	Benefit
	SO4. Training	[25,28,32,40,41]	Benefit
Environmental (EN)	EN1. Environmental management system	[23–26,30,32]	Benefit
	EN2. Green materials and technologies	[7,8,25,26,42]	Benefit
	EN3. Land and water pollution management	[7,24–27,30,32]	Benefit
	EN4. Recycling	[23,25,30,32]	Benefit

2.2. MCDM-Techniques-Based Approaches for Supporting Sustainable Supplier Selection

With the introduction of the sustainability aspect into the supplier selection problem, the complexity of this form of decision making is increased, because businesses need to consider environmental and social aspects related to suppliers rather than just focusing on the suppliers' economic value. Choosing the most potentially sustainable supplier from a set of alternatives in the supply chain under various criteria can be achieved using a wide range of MCDM methods or combinations of methods. Many researchers have already used various models and methodologies for SSS in different industries. Luthra et al. [39] proposed AHP and VIKOR (ViseKriterijumska Optimizacija I Kompromisno Resenje) methods for an SSS problem in the automotive industry. Azimifard et al. [43] combined AHP and TOPSIS (technique for order preference by similarity to ideal solution) techniques for Iran's steel industry, to select the most sustainable suppliers. Stević et al. [25] applied a new MCDM method called measurement of alternatives and ranking according to compromise solution (MARCOS) for SSS in healthcare industries. Petrudi et al. [44] evaluated suppliers in the manufacturing sector considering TBL dimensions, during the COVID-19 disaster, using the BWM method and grey relational analysis (GRA). Yazdani et al. employed stepwise weight assessment ratio analysis (SWARA), level-based weight assessment (LBWA), and MARCOS methods in a sustainable food supplier selection model.

Other strategies that enable decision making in the situation of erroneous or unclear information have begun to be employed, due to the use of multiple qualitative factors in SSS (environmental and social factors are intangible). These techniques are based on the use of fuzzy set theory. Because real-world scenarios are not fully described, and it is challenging to specify the set's limits, the idea of fuzzy sets is more similar to human thinking. With this in mind, Büyüközkan and Çifçi [29] proposed a fuzzy AHP method for SSS in the white goods industry. Azadi et al. [45] used a fuzzy data envelopment analysis (DEA) for SSS in the petrochemical industry. Awasthi et al. [8] used fuzzy AHP and fuzzy VIKOR for SSS in the electronics sector. Tong et al. proposed fuzzy TOPSIS for SSS in the chemical industry. Hendiani et al. [40] used the fuzzy best–worst method (BWM) to prioritize suppliers based on their performance in sustainable development for refineries in Iran. Tong et al. presented a maintenance supplier performance evaluation based on an extended fuzzy PROMETHEE II approach in the petrochemical industry. Orji and Ojadi [42] presented a combined framework of fuzzy AHP and MULTIMOORA (multi-objective optimization based on ratio analysis) for SSS in manufacturing. Wu et al. [26] employed fuzzy grey relational analysis (FGRA), failure mode and effects analysis (FMEA), a cloud computing entropy weight method (EWM), and the decision making trial and evaluation laboratory (DEMATEL) for SSS in the chemical industry. Fallahpour et al. used fuzzy BWM and a fuzzy inference system (FIS) for SSS in the textile industry. Khan and Ali [46] used interpretive structural modeling (ISM) and fuzzy VIKOR for SSS in the cold chain. Olugu et al. [47] employed spherical fuzzy Delphi and TOPSIS techniques for sustainable maintenance management in the oil and gas industry. Wang et al. [48]

optimized the selection of sustainable battery suppliers based on triangular fuzzy entropy and MULTIMOORA methods. A brief literature review summary of MCDM methods for SSS is presented in Table 2.

Table 2. A brief literature review summary of MCDM methods for SSS.

Authors	Year	MCDM Techniques	Industry
Büyüközkan and Çifçi [29]	2011	Fuzzy AHP	White goods
Azadi et al. [45]	2015	Fuzzy DEA	Petrochemical
Luthra et al. [39]	2017	AHP and VIKOR	Automotive
Jain et al. [49]	2018	AHP and TOPSIS	Automotive
Awasthi et al. [8]	2018	Fuzzy AHP and Fuzzy VIKOR	Electronics
Azimifard et al. [43]	2018	AHP and TOPSIS	Steel
Memari et al. [7]	2019	Intuitionistic fuzzy TOPSIS	Manufacturing
Tong et al. [50]	2019	Fuzzy TOPSIS	Chemical
Stević et al. [25]	2019	MARCOS	Healthcare
Hendiani et al. [40]	2020	Fuzzy BWM	Refineries
Tong et al. [51]	2020	Fuzzy PROMETHEE II	Petrochemical
Orji and Ojadi [42]	2021	Fuzzy AHP and MULTIMOORA	Manufacturing
Wu et al. [26]	2021	FGRA, FMEA, EWM, DEMATEL	Chemical
Petrudi et al. [44]	2021	BWM and GRA	Manufacturing
Fallahpour et al. [52]	2021	Fuzzy BWM and FIS	Textile
Yazdani et al. [53]	2021	SWARA, LBWA, MARCOS	Food
Khan and Ali [46]	2021	ISM and Fuzzy VIKOR	Cold chain
Olugu et al. [47]	2021	Spherical fuzzy Delphi and TOPSIS	Oil and gas
Wang et al. [48]	2021	Triangular fuzzy entropy and MULTIMOORA	Battery
Hoseini et al.	2021	Fuzzy BWM and FIS	Construction

2.3. Research Gaps

It can be deduced from the literature review that studies on SSS in the chemical sector in Vietnam are absent from the literature. In light of this, attempts have been made in the current research to use SF-AHP and CoCoSo analysis on the SSS literature data. In fact, to the best of the authors' knowledge, this is the first attempt to apply a hybrid MCDM framework that incorporates the merits of novel spherical fuzzy set theory, AHP, and CoCoSo approaches, which are completely missing from the literature in the context of the Vietnamese chemical industry.

Saaty created the analytical hierarchy process (AHP), which is a robust MCDM approach with several benefits [54]. The technique is used for evaluating, rating, and assessing using criteria, resulting in improved and more predictable judgments. It is one of the most frequently used methods for supplier selection modeling. Although the approach collects data from experts, it may not accurately reflect the expressed opinions. As a result, fuzzy set theory has been combined with AHP, and numerous varieties of fuzzy AHP methods have been devised to capture preference ambiguity. The usefulness of fuzzy AHP approaches has been demonstrated, and researchers and practitioners are becoming more interested. These approaches have been used on many extensions of fuzzy set theory that are dependent on the determination of linguistic assertions, such as traditional fuzzy sets [8,27,42,49,55,56], type-2 fuzzy sets [57–59], interval-valued fuzzy sets [60], intuitionistic fuzzy sets [7], neutrosophic sets [61], Pythagorean fuzzy sets (PSF) [62], and spherical fuzzy sets [15–17]. The spherical fuzzy set (SFS) is a novel set introduced in 2018 by Kutlu Gündoğdu and Kahraman [10,11,63,64]. It is a three-dimensional fuzzy set, consisting of Pythagorean and neutrosophic fuzzy sets combined. SFS may also be used to create criteria for coping with ambiguity and fuzziness in linguistic expressions, giving decision makers a new viewpoint in a hazy situation. Regardless of the membership and non-membership levels of the components in these sets, the decision maker's indeterminacy level is established. In SFS, decision makers specify the membership function on a spherical surface in order to infer additional fuzzy sets from which the parameters of this membership function can be determined in a broader domain.

To reach a compromise solution, therefore, some familiar MCDM methods such as TOPSIS, VIKOR, EDAS (evaluation based on distance from average solution), COPRAS (complex proportional assessment of alternatives), and CODAS (combinative distance-based assessment) have been proposed. Nevertheless, due to differences in the weight distributions of the criteria, various techniques may provide different ranking outcomes for the same problem [65]. As a result, the findings produced using these approaches may be perplexing. To solve this problem, the CoCoSo technique, which is a ranking MCDM approach, is used to assess options based on given indicators. CoCoSo is a novel MCDM ranking model developed by Yazdani, Zarate, Zavadskas, and Turskis in 2019 [66], which is based on the combination of three compromise score aggregation functions [18,67]. Due to its excellent accuracy in computing the ideal compromise score utilizing an integrated framework, the method has been widely adopted by various researchers in different industries. Torkayesh et al. (2021) [22] employed CoCoSo to implement a comparative assessment of social sustainability performance. The method was used for the evaluation of healthcare sectors in Eastern Europe in 2021 [21]. Ecer and Pamucar (2021) [18] combined CoCoSo and fuzzy BWM for selecting suppliers in the home appliance manufacturing industry in Serbia. Cui et al. (2021) [68] used fuzzy SWARA and CoCoSo to evaluate the barriers to IoT implementation in the manufacturing sector. Jahan et al. (2022) [69] used CoCoSo to address the issue of material selection.

The contributions of our research are as follows:

- In practice, this is the first research study in the context of the Vietnamese chemical industry to perform a comprehensive sustainable supplier selection (SSS) procedure. Significant characteristics of TBL within the context are investigated and finalized by means of a literature review and experts' opinions, as are the general sustainability requirements based on the three pillars of sustainability (economic, environmental, and social) in the Vietnamese chemical industry. This is an important benefit of this work.
- Within the literature of MCDM methods, this study is the first to design an integrated SF-AHP and CoCoSo methodology for SSS. The MCDM method is implemented with the aid of experts' inputs.
- A real case study is performed to evaluate the performances of five suppliers in terms of achieving social sustainability goals.
- With regard to managerial implications, our proposed approach and results could form a basis for making informed decisions that help firms to achieve supply chain sustainability, to capture opportunities, and to maintain competitiveness through reconfiguring resources. The method may be useful for case studies in other countries and other sustainability problems.

3. Materials and Methods

In this study, a two-phase MCDM-model-based strategy was used for studying supplier selection in the chemical sector. The list of criteria was developed using the literature and expert opinions. The framework's applicability was demonstrated in a case study in the Vietnamese chemical industry. First, the SF-AHP model was used to establish the criteria. The alternatives were then ranked using the CoCoSo model in the order of their significance level. To reduce uncertainty in decision making, the spherical fuzzy set was coupled. A consistency test was used to ensure that the expert evaluation process was consistent. A sensitivity analysis was also carried out to demonstrate the resilience of the proposed MCDM model. Figure 1 displays the proposed MCDM framework employed in this study.

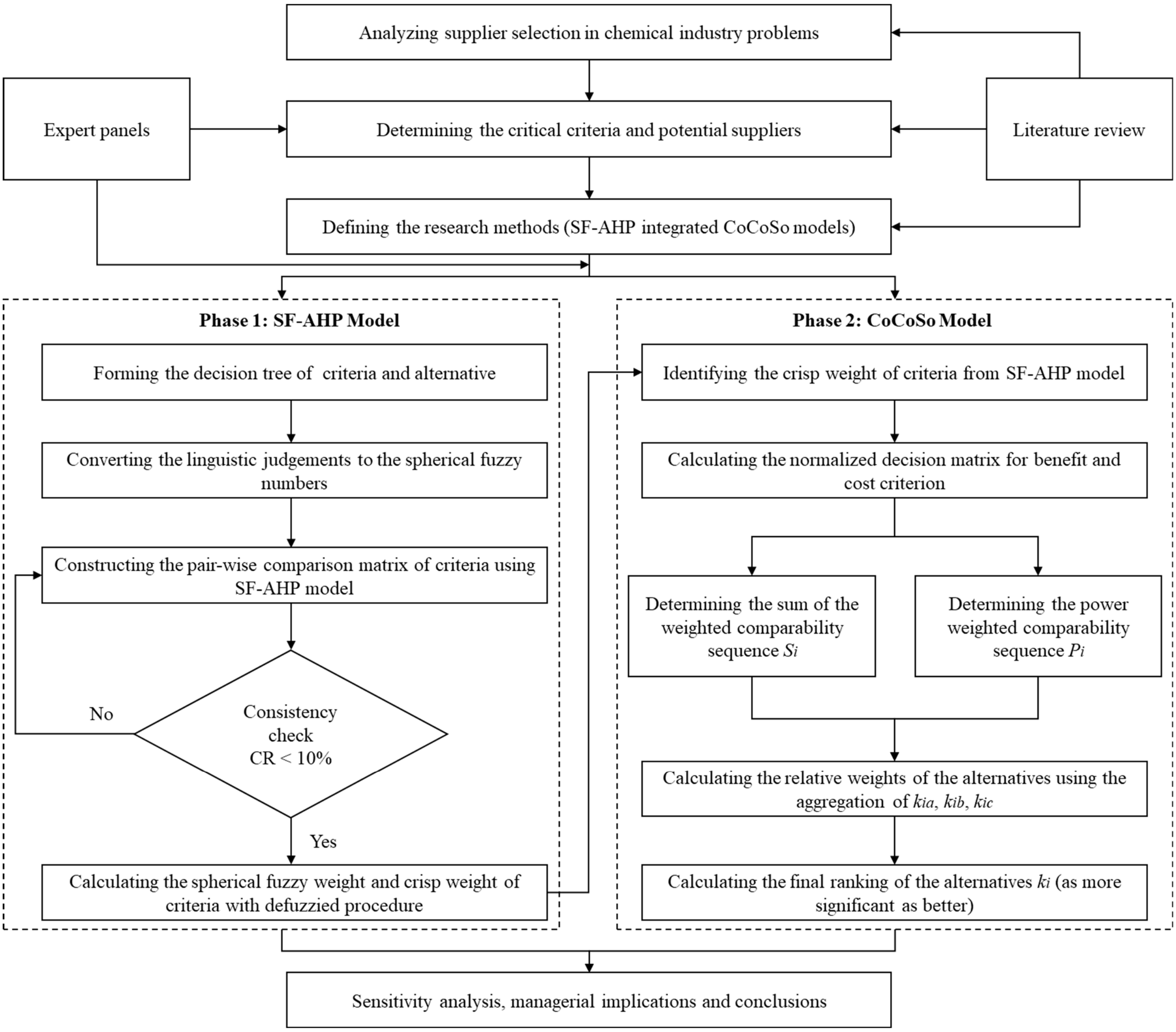

Figure 1. The proposed MCDM framework.

3.1. Spherical Fuzzy Analytical Hierarchy Process (SF-AHP)

Spherical fuzzy sets (SFS) were first proposed by Kutlu Gündoudu and Kahraman [10]. Each spherical fuzzy number includes the membership, non-membership, and hesitancy functions from the interval [0, 1] [64].

Definition 1. *A single-value SFS $\widetilde{F}_S$ in the universe of discourse X is given by Equations (1)–(3).*

$$\widetilde{F}_S = \left\{ x, \left(\alpha_{\widetilde{F}_S}(x),\ \beta_{\widetilde{F}_S}(x),\ \gamma_{\widetilde{F}_S}(x) \right) \middle| x \in X \right\} \tag{1}$$

$$\alpha_{\widetilde{F}_S}(x):\ X \to [0,1], \beta_{\widetilde{F}_S}(x) : X \to [0,1], \gamma_{\widetilde{F}_S}(x) : X \to [0,1] \tag{2}$$

$$0 \le \alpha^2_{\widetilde{F}_S}(x) + \beta^2_{\widetilde{F}_S}(x) + \gamma^2_{\widetilde{F}_S}(x) \le 1 \tag{3}$$

with $\forall x \in X$. For each x,$\alpha_{\widetilde{F}_S}(x)$, $\beta_{\widetilde{F}_S}(x)$, and $\gamma_{\widetilde{F}_S}(x)$ denote the membership, non-membership, and hesitancy levels of x in $\widetilde{F}_S$, respectively.

Definition 2. *For convenience, let* $\widetilde{F}_S = \left(\alpha_{\widetilde{F}_S}, \beta_{\widetilde{F}_S}, \gamma_{\widetilde{F}_S}\right)$ *and* $\widetilde{E}_S = \left(\alpha_{\widetilde{E}_S}, \beta_{\widetilde{E}_S}, \gamma_{\widetilde{E}_S}\right)$ *be two SFSs. Some arithmetic operations of SFSs are presented in Equations (4)–(9):*

- *Union operation*

$$\widetilde{F}_S \cup \widetilde{E}_S = \Big\{ max\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\}, min\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\}, min\{(1-((max\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\})^2 + (min\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\})^2))^{1/2}, max\{\gamma_{\widetilde{F}_S}, \gamma_{\widetilde{E}_S}\}\Big\} \tag{4}$$

- *Intersection operation*

$$\widetilde{F}_S \cap \widetilde{E}_S = \Big\{ min\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\}, max\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\}, max\{(1-((min\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\})^2 + (max\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\})^2))^{1/2}, min\{\gamma_{\widetilde{F}_S}, \gamma_{\widetilde{E}_S}\}\}\Big\} \tag{5}$$

- *Addition operation*

$$\widetilde{F}_S \oplus \widetilde{E}_S = \left\{ \left(\alpha^2_{\widetilde{F}_S} + \alpha^2_{\widetilde{E}_S} - \alpha^2_{\widetilde{F}_S}\alpha^2_{\widetilde{E}_S}\right)^{1/2}, \beta_{\widetilde{F}_S}\beta_{\widetilde{E}_S}, \left(\left(1-\alpha^2_{\widetilde{E}_S}\right)\gamma^2_{\widetilde{F}_S} + \left(1-\alpha^2_{\widetilde{F}_S}\right)\gamma^2_{\widetilde{E}_S} - \gamma^2_{\widetilde{F}_S}\gamma^2_{\widetilde{E}_S}\right)^{1/2} \right\} \tag{6}$$

- *Multiplication operation*

$$\widetilde{F}_S \otimes \widetilde{E}_S = \left\{ \alpha^2_{\widetilde{F}_S}\alpha^2_{\widetilde{E}_S}, \left(\beta^2_{\widetilde{F}_S} + \beta^2_{\widetilde{E}_S} - \beta^2_{\widetilde{F}_S}\beta^2_{\widetilde{E}_S}\right)^{1/2}, \left(\left(1-\beta^2_{\widetilde{E}_S}\right)\gamma^2_{\widetilde{F}_S} + \left(1-\beta^2_{\widetilde{F}_S}\right)\gamma^2_{\widetilde{E}_S} - \gamma^2_{\widetilde{F}_S}\gamma^2_{\widetilde{E}_S}\right)^{1/2} \right\} \tag{7}$$

- *Multiplication by a scalar;* $\sigma > 0$

$$\sigma \cdot \widetilde{F}_S = \left\{ (1-(1-\alpha^2_{\widetilde{F}_S})^{\sigma})^{1/2}, \beta^{\sigma}_{\widetilde{F}_S}, ((1-\alpha^2_{\widetilde{F}_S})^{\sigma} - (1-\alpha^2_{\widetilde{F}_S} - \gamma^2_{\widetilde{F}_S})^{\sigma})^{1/2} \right\} \tag{8}$$

- *Power of* F_S; $\sigma > 0$

$$\widetilde{F}^{\sigma}_S = \left\{ \alpha^{\sigma}_{\widetilde{F}_S}, (1-(1-\beta^2_{\widetilde{F}_S})^{\sigma})^{1/2}, ((1-\beta^2_{\widetilde{F}_S})^{\sigma} - (1-\beta^2_{\widetilde{F}_S} - \gamma^2_{\widetilde{F}_S})^{\sigma})^{1/2} \right\} \tag{9}$$

Definition 3. *For these SFSs, with* $\widetilde{F}_S = \left(\alpha_{\widetilde{F}_S}, \beta_{\widetilde{F}_S}, \gamma_{\widetilde{F}_S}\right)$ *and* $\widetilde{E}_S = \left(\alpha_{\widetilde{E}_S}, \beta_{\widetilde{E}_S}, \gamma_{\widetilde{E}_S}\right)$, *the following equations are valid under the condition* $\sigma, \sigma_1, \sigma_2 > 0$ *(Equations (10)–(15)):*

$$\widetilde{F}_S \oplus \widetilde{E}_S = \widetilde{E}_S \oplus \widetilde{F}_S \tag{10}$$

$$\widetilde{F}_S \otimes \widetilde{E}_S = \widetilde{E}_S \otimes \widetilde{F}_S \tag{11}$$

$$\sigma\left(\widetilde{F}_S \oplus \widetilde{E}_S\right) = \sigma\widetilde{F}_S \oplus \sigma\widetilde{E}_S \tag{12}$$

$$\sigma_1\widetilde{F}_S \oplus \sigma_2\widetilde{F}_S = (\sigma_1 + \sigma_2)\widetilde{F}_S \tag{13}$$

$$(\widetilde{F}_S \otimes \widetilde{E}_S)^{\sigma} = \widetilde{F}^{\sigma}_S \otimes \widetilde{E}^{\sigma}_S \tag{14}$$

$$\widetilde{F}^{\sigma_1}_S \otimes \widetilde{F}^{\sigma_2}_S = \widetilde{F}^{\sigma_1+\sigma_2}_S \tag{15}$$

Definition 4. *The spherical weighted arithmetic mean (SWAM) with respect to* $w = (w_1, w_2, \ldots, w_n)$; $w_i \in [0, 1]$; $\sum_{i=1}^{n} w_i = 1$, *is defined by Equation (16).*

$$SWAM_w\left(\widetilde{F}_{S1},\ldots,\ \widetilde{F}_{Sn}\right) = w_1\widetilde{F}_{S1} + w_2\widetilde{F}_{S2} + \ldots + w_n\widetilde{F}_{Sn} = \left\{ \left[1 - \prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}}\right)^{w_i}\right]^{1/2}, \prod_{i=1}^{n}\beta^{w_i}_{\widetilde{F}_{Si}}, \left[\prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}}\right)^{w_i} - \prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}} - \gamma^2_{\widetilde{F}_{Si}}\right)^{w_i}\right]^{1/2} \right\} \quad (16)$$

In this study, the SF-AHP model was used to calculate the criteria weights. The SF-AHP model consists of six steps, as follows [14].

Step 1: The hierarchical structure is organized with the research goal (level 1) and the list of criteria $C = \{C_1,\ C_2, \ldots C_n\}$ (level 2) within $n \geq 2$.

Step 2: The pairwise comparison matrices are constructed with respect to spherical fuzzy linguistic scales, as shown in Table 3. The score indices (SI) are determined by Equations (17) and (18):

$$SI = \sqrt{\left|100 * \left[\left(\alpha_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S}\right)^2 - \left(\beta_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S}\right)^2\right]\right|} \quad (17)$$

for AMI, VHI, HI, SMI, and EI, and

$$\frac{1}{SI} = \frac{1}{\sqrt{\left|100 * \left[\left(\alpha_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S}\right)^2 - \left(\beta_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S}\right)^2\right]\right|}} \quad (18)$$

for EI, SLI, LI, VLI, and ALI.

Table 3. SF-AHP linguistic scales used for the pairwise comparisons.

Linguistics Scale	Fuzzy Number (α,β,γ)	Score Index (SI)
Extremely high importance (AMI)	(0.9, 0.1, 0.0)	9
Very high importance (VHI)	(0.8, 0.2, 0.1)	7
High importance (HI)	(0.7, 0.3, 0.2)	5
Slightly high importance (SMI)	(0.6, 0.4, 0.3)	3
Equal importance (EI)	(0.5, 0.4, 0.4)	1
Slightly low importance (SLI)	(0.4, 0.6, 0.3)	1/3
Low importance (LI)	(0.3, 0.7, 0.2)	1/5
Very low importance (VLI)	(0.2, 0.8, 0.1)	1/7
Extremely low importance (ALI)	(0.1, 0.9, 0.0)	1/9

Step 3: The linguistics scales are converted to the corresponding SI. Then, the consistency ratio (CR) is checked for the pairwise comparison matrices, where the CR must be less than 10%.

Step 4: The weight of each criterion is determined using the $SWAM$ operator, as in Equation (19).

$$SWAM_w\left(\widetilde{F}_{S1},\ldots,\ \widetilde{F}_{Sn}\right) = w_1\widetilde{F}_{S1} + w_2\widetilde{F}_{S2} + \ldots + w_n\widetilde{F}_{Sn} = \left\{ \left[1 - \prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}}\right)^{w_i}\right]^{1/2}, \prod_{i=1}^{n}\beta^{w_i}_{\widetilde{F}_{Si}}, \left[\prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}}\right)^{w_i} - \prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}} - \gamma^2_{\widetilde{F}_{Si}}\right)^{w_i}\right]^{1/2} \right\} \quad (19)$$

where $w = 1/n$.

Step 5: The criterion weights are defuzzified using Equation (20). Then, they are normalized using Equation (21). The multiplication operator in Equation (22) is applied to aggregate the final ranking scores.

$$S\left(\widetilde{w}_j^s\right) = \sqrt{\left|100 * \left[\left(3\alpha_{\widetilde{F}_S} - \frac{\gamma_{\widetilde{F}_S}}{2}\right)^2 - \left(\frac{\beta_{\widetilde{F}_S}}{2} - \gamma_{\widetilde{F}_S}\right)^2\right]\right|} \quad (20)$$

$$\overline{w}_j^s = \frac{S\left(\widetilde{w}_j^s\right)}{\sum_{j=1}^n S\left(\widetilde{w}_j^s\right)} \quad (21)$$

$$\widetilde{F}_{S_{ij}} = \overline{w}_j^s . \widetilde{F}_{S_i} = \left\{\left(1-\left(1-\alpha_{\widetilde{F}_S}^2\right)^{\overline{w}_j^s}\right)^{1/2}, \beta_{\widetilde{F}_S}^{\overline{w}_j^s}, \left(\left(1-\alpha_{\widetilde{F}_S}^2\right)^{\overline{w}_j^s} - \left(1-\alpha_{\widetilde{F}_S}^2-\gamma_{\widetilde{F}_S}^2\right)^{\overline{w}_j^s}\right)^{1/2}\right\}, \forall i \quad (22)$$

The final SF-AHP score ($\widetilde{F}$) is calculated by carrying out spherical fuzzy arithmetical addition over global weights, as given in Equation (23).

$$\widetilde{F} = \sum_{j=1}^{n} \widetilde{F}_{S_{ij}} = \widetilde{F}_{S_{i1}} \oplus \widetilde{F}_{S_{i2}} \oplus \ldots \oplus \widetilde{F}_{S_{in}}, \forall i$$
$$\text{i.e., } \widetilde{F}_{S_{11}} \oplus \widetilde{F}_{S_{12}} = \left\{\left(\alpha_{\widetilde{F}_{S_{11}}}^2 + \alpha_{\widetilde{F}_{S_{12}}}^2 - \alpha_{\widetilde{F}_{S_{11}}}^2 \alpha_{\widetilde{F}_{S_{12}}}^2\right)^{1/2}, \beta_{\widetilde{F}_{S_{11}}} \beta_{\widetilde{F}_{S_{12}}}, \left(\left(1-\alpha_{\widetilde{F}_{S_{12}}}^2\right)\gamma_{\widetilde{F}_{S_{11}}}^2 + \left(1-\alpha_{\widetilde{F}_{S_{11}}}^2\right)\gamma_{\widetilde{F}_{S_{12}}}^2 - \gamma_{\widetilde{F}_{S_{11}}}^2 \gamma_{\widetilde{F}_{S_{12}}}^2\right)^{1/2}\right\} \quad (23)$$

Step 6: The final score of each criterion is defuzzified. The criteria weights in this phase are used for the CoCoSo model in the next phase.

3.2. Combined Compromise Solution (CoCoSo)

The combined compromise solution (CoCoSo) method in the proposed approach was built based on an integrated exponentially weighted product and a simple additive weighting model. It may be a compendium of compromise solutions. After defining the criteria and alternatives, the CoCoSo process is as presented step by step below [66].

Step 1: A decision matrix is constructed as in Equation (24).

$$X = \left[x_{ij}\right]_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{bmatrix}; \; i = 1,2,\ldots,m; \; j = 1,2\ldots n \quad (24)$$

where x_{ij} is the performance of the ith alternative to the jth criterion, m is the number of alternatives, and n is the number of criteria.

Step 2: The compromise normalization Equations (25) and (26) are used to normalize the values of the criteria.

$$r_{ij} = \frac{x_{ij} - min_i x_{ij}}{max_i x_{ij} - min_i x_{ij}}; \text{ for benefit criterion} \quad (25)$$

$$r_{ij} = \frac{max_i x_{ij} - x_{ij}}{max_i x_{ij} - min_i x_{ij}}; \text{ for cos t criterion} \quad (26)$$

Step 3: The sum of the weighted comparability sequence S_i and the total of the power-weighted comparability sequence P_i for each alternative are calculated using Equations (27) and (28), respectively.

$$S_i = \sum_{j=1}^{n} \left(w_j r_{ij}\right) \quad (27)$$

$$P_i = \sum_{j=1}^{n} \left(r_{ij}\right)^{w_j} \quad (28)$$

Step 4: The relative weights of the alternatives are calculated based on the following aggregating strategies. Three performance score strategies are applied in this stage to calculate the relative weights of other options. The arithmetic means of the sums of the WSM (weighted sum method) and WPM (weighted product method) scores are expressed by Equation (29).

$$k_{ia} = \frac{S_i + P_i}{\sum_{i=1}^{m}(P_i + S_i)} \quad (29)$$

Equation (30) is the sum of the relative scores of WSM and WPM compared to the best.

$$k_{ib} = \frac{S_i}{min_i S_i} + \frac{P_i}{min_i P_i} \quad (30)$$

Equation (31) generates a balanced compromise of the WSM and WPM model scores, as follows. In this study, the value of λ was considered to be 0.5 ($\lambda = 0.5$) for beginning the analysis.

$$k_{ic} = \frac{\lambda(S_i) + (1-\lambda)(P_i)}{\lambda max_i S_i + (1-\lambda) max_i P_i};\ 0 \leq \lambda \leq 1 \quad (31)$$

Step 5: The final ranking of the alternatives is calculated based on the k_i value, i.e., the appraisal score (the more significant the better), as can be seen in Equation (32). The optimal alternative is the one with the highest appraisal score in the CoCoSo model.

$$k_i = (k_{ia}k_{ib}k_{ic})^{\frac{1}{3}} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic}) \quad (32)$$

4. Results Analysis

4.1. A Case Study in the Chemical Industry in Vietnam

This study used a two-phase MCDM model, integrating the SF-AHP and CoCoSo models to assess and choose acceptable suppliers in terms of sustainability (compromised economic, social, and environmental issues). As shown in Table 4, a case study of five chemical suppliers in Vietnam was utilized to evaluate the suggested model. The suppliers were: Duc Giang Chemicals Group Joint Stock Company (CHE-01), Ho Chi Minh Chemical Joint Stock Company (CHE-02), South Basic Chemicals Joint Stock Company (CHE-03), Viet Tri Chemical Joint Stock Company (CHE-04), and Vietnam National Chemical Group (CHE-05). The sustainable criteria were determined through interviews with professionals with previous management experience, particularly in the chemical industry in Vietnam, as shown in Table 5. The hierarchical structure of this study is visualized in Figure 2.

Table 4. The list of suppliers.

No.	Company	Symbol	Website (accessed on 7 April 2022)
1	Duc Giang Chemicals Group Joint Stock Company	CHE-01	http://www.ducgiangchem.vn/
2	Ho Chi Minh Chemical Joint Stock Company	CHE-02	https://www.hcmc.com.vn/
3	South Basic Chemicals Joint Stock Company	CHE-03	https://sochemvn.com/
4	Viet Tri Chemical Joint Stock Company	CHE-04	http://vitrichem.vn/
5	Vietnam National Chemical Group	CHE-05	http://www.vinachem.com.vn/

Table 5. The professionals interviewed.

Category	Profile	No. of Respondents
Education level	BSc in Supply Chain Management/Industrial Engineering/ Chemical Engineering	8
	MSc in Supply Chain Management/Industrial Systems Engineering and Management/Chemical Engineering	4
	PhD in Supply Chain Management/Industrial Systems Engineering and Management/Chemical Engineering	3

Table 5. *Cont.*

Category	Profile	No. of Respondents
Work experience	Between five and ten years	10
	More than ten years	5
Work field	Chemical companies	6
	Chemical logistics companies	2
	Research	7

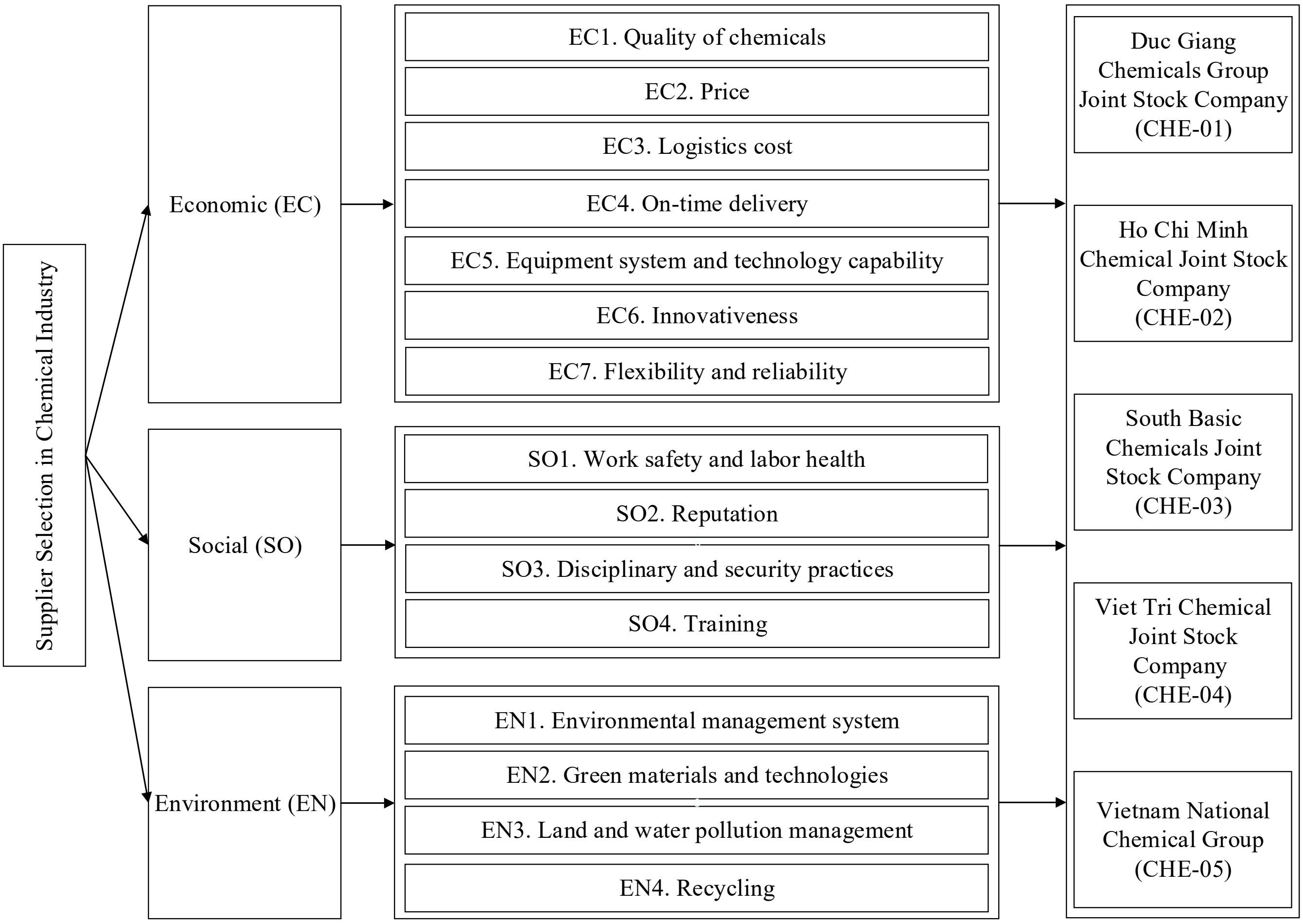

Figure 2. Hierarchical structure.

4.2. SF-AHP Model for Determination of Criteria Weights

The SF-AHP model uses the following step-by-step calculation process (as an example) for the three main dimensions, which are economic (EC) (criterion C1 in the example), social (SO) (criterion C2 in the example), and environmental (EN) (criterion C3 in the example). The pairwise comparison matrix, the non-fuzzy comparison matrix, and the normalized comparison matrix of the three main dimensions are shown in Tables 6–8. The consistency ratio of the pairwise comparison was calculated accordingly. Note that WSV is the weighted sum value, CV is the consistency vector, C is the considered criteria, and SI is the score index.

$$C_{12} = \frac{SI_{C_{12}}}{SUM_{C_2}} = \frac{0.6366}{3.0081} = 0.2116$$

$$MEAN_{C_1} = \frac{0.2719+0.2116+0.3432}{3} = 0.2756$$

$$WSV = \begin{bmatrix} 1.0000 & 0.6366 & 0.9036 \\ 1.5708 & 1.0000 & 0.7291 \\ 1.1067 & 1.3715 & 1.0000 \end{bmatrix} \times \begin{bmatrix} 0.2756 \\ 0.3455 \\ 0.3789 \end{bmatrix} = \begin{bmatrix} 0.8379 \\ 1.0547 \\ 1.1578 \end{bmatrix};$$

$$CV = \begin{bmatrix} 0.8379 \\ 1.0547 \\ 1.1578 \end{bmatrix} / \begin{bmatrix} 0.2756 \\ 0.3455 \\ 0.3789 \end{bmatrix} = \begin{bmatrix} 3.0405 \\ 3.0526 \\ 3.0556 \end{bmatrix}$$

With three main dimensions ($n = 3$), the largest eigenvector (λ_{max}) was calculated to identify the consistency index (CI), the random index (RI), and consistency ratio (CR) as follows:

$$\lambda_{max} = \frac{3.0405+3.0526+3.0556}{3} = 3.0495$$

$$CI = \frac{\lambda_{max}-n}{n-1} = \frac{3.0495-3}{3-1} = 0.0248$$

For $n = 3$ and $RI = 0.58$, the CR value is calculated as follows:

$$CR = \frac{CI}{RI} = \frac{0.0248}{0.58} = 0.0427 \approx 4.27\%$$

As shown by the fact that $CR = 4.27\% < 10\%$, the pairwise comparison matrix was consistent, and the result was satisfactory.

Table 6. The pairwise comparison matrix of SF-AHP.

Dimension	Left Criterion Is Greater					Right Criterion Is Greater				Dimension
	AMI	VHI	HI	SMI	EI	SLI	LI	VLI	ALI	
C1		2	1	2	1	2	4	3		C2
C1			3	3	3	2	1	3		C3
C2		1	2	3	1	2	2	4		C3

Table 7. The non-fuzzy comparison matrix of SF-AHP.

Dimension	C1	C2	C3
C1	1.0000	0.6366	0.9036
C2	1.5708	1.0000	0.7291
C3	1.1067	1.3715	1.0000
SUM	3.6775	3.0081	2.6327

Table 8. The normalized comparison matrix of SF-AHP.

Dimension	C1	C2	C3	*MEAN*	*WSV*	*CV*
C1	0.2719	0.2116	0.3432	0.2756	0.8379	3.0405
C2	0.4271	0.3324	0.2769	0.3455	1.0547	3.0526
C3	0.3009	0.4559	0.3798	0.3789	1.1578	3.0556

Note: WSV is the weighted sum value and CV is the consistency vector.

The integrated spherical fuzzy comparison matrix was calculated, as can be seen in Table 9. Then, the obtained spherical fuzzy weight of each dimension was calculated, as can be seen in Table 10. For better understanding, the following calculation is shown for the calculation of the spherical fuzzy weights of the social criterion (C1), with spherical fuzzy weights $(\alpha, \beta, \gamma) = (0.4455,\ 0.5224,\ 0.3105)$, as follows:

$$\alpha_{C1} = \left[1 - \prod_{i=1}^{n} (1 - \alpha_{\tilde{F}_{Si}}^{2})^{w_i}\right]^{1/2} = \left[1 - \left(1 - 0.5000^2\right)^{\frac{1}{3}} * \left(1 - 0.3934^2\right)^{\frac{1}{3}} * \left(1 - 0.4332^2\right)^{\frac{1}{3}}\right]^{1/2} = 0.4455$$

$$\beta_{C1} = \prod_{i=1}^{n} \beta_{\tilde{F}_{Si}}^{w_i} = 0.4000^{\frac{1}{3}} * 0.6224^{\frac{1}{3}} * 0.5726^{\frac{1}{3}} = 0.5224$$

$$\gamma_{C1} = \left[\prod_{i=1}^{n} (1 - \alpha_{\tilde{F}_{Si}}^{2})^{w_i} - \prod_{i=1}^{n} (1 - \alpha_{\tilde{F}_{Si}}^{2} - \gamma_{\tilde{F}_{Si}}^{2})^{w_i}\right]^{1/2}$$
$$= \left[\left(1 - 0.5000^2\right)^{\frac{1}{3}} * \left(1 - 0.3934^2\right)^{\frac{1}{3}} * \left(1 - 0.4332^2\right)^{\frac{1}{3}} - \left(1 - 0.5000^2 - 0.4000^2\right)^{\frac{1}{3}}\right.$$
$$\left. * \left(1 - 0.3934^2 - 0.2186^2\right)^{\frac{1}{3}} * \left(1 - 0.4332^2 - 0.2591^2\right)^{\frac{1}{3}}\right]^{1/2} = 0.3105$$

$$S\left(\tilde{w}_{C1}^{s}\right) = \sqrt{\left|100 * \left[\left(3\alpha_{\tilde{F}_S} - \frac{\gamma_{\tilde{F}_S}}{2}\right)^2 - \left(\frac{\beta_{\tilde{F}_S}}{2} - \gamma_{\tilde{F}_S}\right)^2\right]\right|} = \sqrt{\left|100 * \left[\left(3 * 0.445 - \frac{0.3105}{2}\right)^2 - \left(\frac{0.5224}{2} - 0.3105\right)^2\right]\right|}$$
$$= 11.8023$$

$$\overline{w}_{C1}^{s} = \frac{S\left(\tilde{w}_j^s\right)}{\sum_{j=1}^{n} S\left(\tilde{w}_j^s\right)} = \frac{11.8023}{11.8023 + 12.6112 + 13.1789} = 0.3140$$

Table 9. The integrated spherical fuzzy comparison matrix.

Dimension	C1			C2			C3		
	α	β	γ	α	β	γ	α	β	γ
C1	0.5000	0.4000	0.4000	0.3934	0.6224	0.2186	0.4332	0.5726	0.2591
C2	0.5036	0.5208	0.2289	0.5000	0.4000	0.4000	0.3974	0.6192	0.2204
C3	0.4753	0.5227	0.2808	0.5029	0.5184	0.2413	0.5000	0.4000	0.4000

Table 10. The spherical weights from SF-AHP.

Dimension	SF-AHP Weight			Calculations to Obtain Crisp Weights	Crisp Weights
	α	β	γ	$S(\tilde{w}_j^s)$	$\overline{w}_j^s$
C1	0.4455	0.5224	0.3105	11.8023	0.3140
C2	0.4709	0.5053	0.3013	12.6112	0.3355
C3	0.4930	0.4768	0.3174	13.1789	0.3506

The crisp weights are calculated accordingly. The most significant criterion is the environmental criterion (C3), with a value of 0.3506, followed by the social criterion (C2) with a value of 0.3355. The economic criterion (C1) is the least significant, with a value of 0.3140. In the same way, the integrated spherical fuzzy comparison matrix with 15 criteria is calculated and shown in Table A1 (Appendix A).

The SF-AHP weights consist of three parameters: the membership function (α), the non-membership function (β), and the hesitancy function (γ) of the element $x \in X$. Table 11 shows the spherical fuzzy weights and crisp weights of SF-AHP. The geometrical mean was used to calculate the importance level of each criterion. According to the results, the spherical fuzzy weights of the criterion "EC1. Quality of chemicals", for example, were membership function (α) = 0.4987, non-membership function (β) = 0.4900, and hesitancy function (γ) = 0.3215, with a crisp weight of 0.0684. A similar procedure was used for the spherical fuzzy weights of the criterion "EC2. Price" which has membership function (α), non-membership function (β), and hesitancy function (γ) values of 0.4925, 0.3295, and 0.0666, respectively, with a crisp weight of 0.4882. The significance levels of 15 criteria of the SF-AHP model are visualized in Figure 3. The results show that the five most significant criteria for qualitative performance evaluation in chemical supplier selection for the case study in Vietnam were "EC5. Equipment system and technology capability", "EC7. Flexibility and reliability", "EC3. Logistics cost", "EN2. Green materials and technologies", and "EC4. On-time delivery", with significance levels of 7.68%, 7.53%, 7.51%, 7.18%, and 7.09%, respectively. "EN4. Recycling" was the least significant criterion, with a value of 4.75%. The findings indicate that decision makers should prioritize EC5, EC7, EC3, EN2, and EC4 for enhancing the performance of chemical suppliers, particularly in the Vietnamese chemical industry.

Table 11. Spherical fuzzy weights and crisp weights of 15 criteria of SF-AHP.

Criteria	Geometric Mean			Spherical Fuzzy Weights			Crisp Weights
	α	β	γ	α	β	γ	
EC1. Quality of chemicals	0.7513	0.4900	0.1033	0.4987	0.4900	0.3215	0.0684
EC2. Price	0.7617	0.4925	0.1086	0.4882	0.4925	0.3295	0.0666
EC3. Logistics cost	0.7080	0.4538	0.0983	0.5404	0.4538	0.3135	0.0751
EC4. On-time delivery	0.7327	0.4728	0.1100	0.5170	0.4728	0.3317	0.0709
EC5. Equipment system and technology capability	0.6941	0.4318	0.1029	0.5531	0.4318	0.3208	0.0768
EC6. Innovativeness	0.7582	0.5026	0.0943	0.4917	0.5026	0.3071	0.0678
EC7. Flexibility and reliability	0.7012	0.4294	0.1121	0.5466	0.4294	0.3349	0.0753
SO1. Work safety and labor health	0.7422	0.4751	0.1130	0.5077	0.4751	0.3362	0.0694
SO2. Reputation	0.8068	0.5598	0.0866	0.4396	0.5598	0.2943	0.0602
SO3. Disciplinary and security practices	0.7942	0.5408	0.0919	0.4537	0.5408	0.3031	0.0621
SO4. Training	0.8479	0.6235	0.0709	0.3900	0.6235	0.2662	0.0532
EN1. Environmental management system	0.7481	0.4847	0.0988	0.5019	0.4847	0.3143	0.0691
EN2. Green materials and technologies	0.7279	0.4659	0.1058	0.5216	0.4659	0.3252	0.0718
EN3. Land and water pollution management	0.7653	0.4867	0.1140	0.4845	0.4867	0.3376	0.0658
EN4. Recycling	0.8783	0.6610	0.0548	0.3489	0.6610	0.2341	0.0475

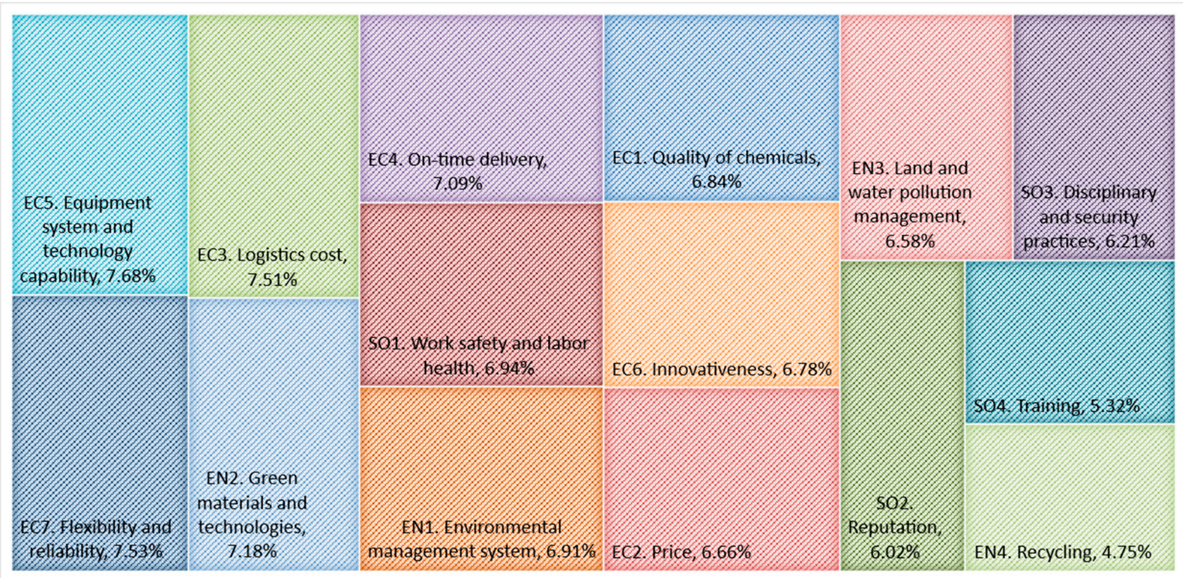

Figure 3. The significance levels of 15 criteria of SF-AHP.

4.3. CoCoSo Model for Ranking Suppliers

The compromise solution in the CoCoSo model is established using a compositive simple additive (SAW) and exponentially weighted product (EWP) model, which can assess and rank the alternatives with a high level of confidence. The SF-AHP model determines the relative weights of the criteria. According to the CoCoSo procedure, from the initial integrated matrix, the normalized matrix, the weighted comparability sequence (Table A2—Appendix A), and the exponentially weighted comparability sequence (Table A3—Appendix A) are calculated, respectively. Finally, the final aggregation and ranking are determined, as can be seen in Table 12. The result suggests that Vietnam National Chemical Group (CHE-05) was the optimal supplier, with the highest score of 3.1039 for sustainability performance in the chemical industry in Vietnam. The South Basic Chemicals Joint Stock Company (CHE-03) was ranked as having the lowest performance, with a score of 1.3068. From the results, the supplier ranking obtained was CHE-05 > CHE-04 > CHE-02 > CHE-01 > CHE-03. The final ranking of suppliers is visualized in Figure 4.

Table 12. The evaluation of the appraisal score of the CoCoSo model.

Alternative	Ka	Ranking	Kb	Ranking	Kc	Ranking	K	Final Ranking
CHE-01	0.2051	4	3.2738	4	0.8154	4	2.2495	4
CHE-02	0.2122	3	3.9158	3	0.8435	3	2.5454	3
CHE-03	0.1099	5	2.0000	5	0.4368	5	1.3068	5
CHE-04	0.2473	1	4.4256	2	0.9831	1	2.9100	2
CHE-05	0.2255	2	5.1492	1	0.8965	2	3.1039	1

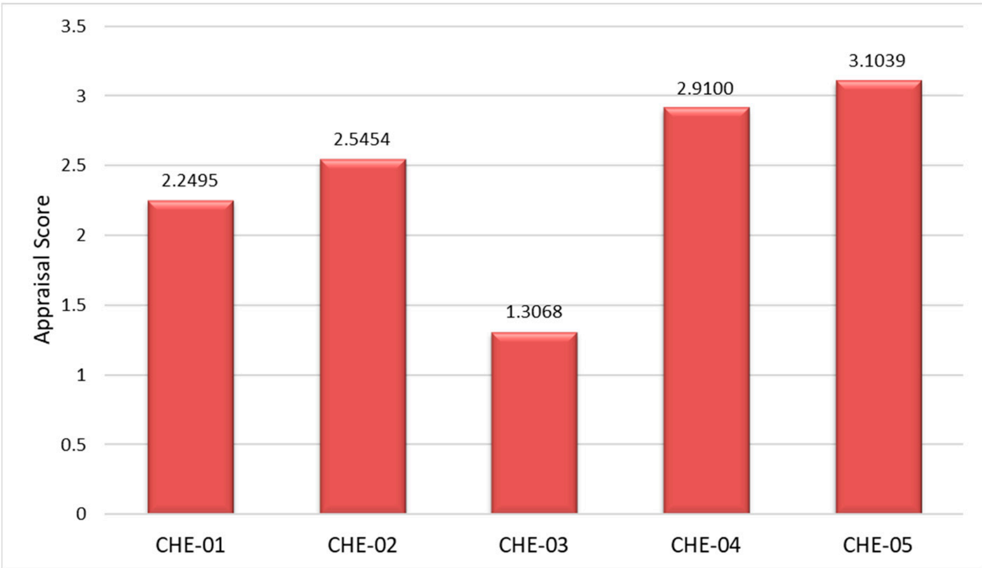

Figure 4. Final ranking of suppliers.

5. Results Validation

5.1. Sensitivity Analysis

To illustrate the resilience and stability of the model in the decision-making process, a sensitivity analysis was performed. For the purposes of this study, the coefficient value (λ) was assumed to be 0.5 ($\lambda = 0.5$). The relevant outcome values were then investigated at the sensitivity analysis stage by adjusting the coefficient value (λ) in the range of 0 to 1, which can affect the findings as predicted. The final performance scores of the CoCoSo model with different λ values are presented in Table 13 and visualized in Figure 5. The results show that no matter how λ changed, Vietnam National Chemical Group (CHE-05) was always the optimal supplier. This means that the values of the coefficient (λ) did not affect the ranking of suppliers. South Basic Chemicals Joint Stock Company (CHE-03) still showed the lowest performance in the evaluation process. Therefore, this demonstrates the reliability and effectiveness of the proposed model.

Table 13. The final performance score of the CoCoSo model with different λ values.

Alternative	Final Appraisal Score										
	λ = 0	λ = 0.1	λ = 0.2	λ = 0.3	λ = 0.4	λ = 0.5	λ = 0.6	λ = 0.7	λ = 0.8	λ = 0.9	λ = 1
CHE-01	2.2639	2.2622	2.2602	2.2576	2.2541	2.2495	2.2428	2.2324	2.2139	2.1716	1.9736
CHE-02	2.5537	2.5527	2.5515	2.5500	2.5481	2.5454	2.5415	2.5355	2.5249	2.5008	2.3937
CHE-03	1.3115	1.3109	1.3103	1.3094	1.3083	1.3068	1.3047	1.3013	1.2953	1.2818	1.2214
CHE-04	2.9215	2.9202	2.9185	2.9164	2.9137	2.9100	2.9047	2.8965	2.8818	2.8485	2.6992
CHE-05	3.0996	3.1001	3.1007	3.1015	3.1025	3.1039	3.1059	3.1089	3.1142	3.1261	3.1760

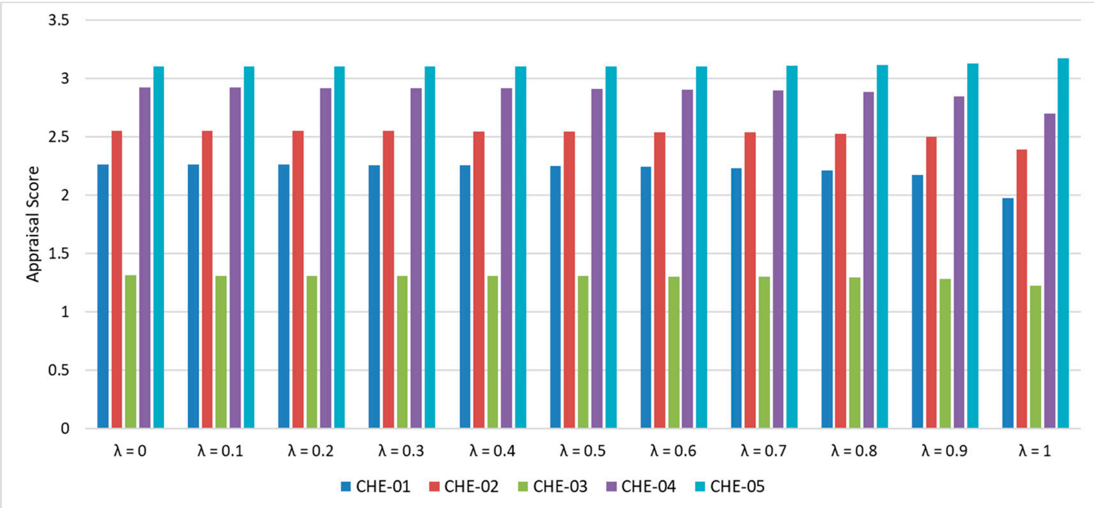

Figure 5. Sensitivity analysis with different λ values.

5.2. Comparison Analysis

A comparison analysis of methods was conducted to verify the value of the method used. In this study, six different MCDM ranking methods were considered to check the results obtained by the proposed model. The ranking of automotive suppliers using the integrated SF-AHP and CoCoSo model was evaluated by comparison with multi-attributive border approximation area comparison (MABAC) [70], evaluation based on distance from average solution (EDAS) [71], weighted aggregated sum product assessment (WASPAS) [66], measurement of alternatives and ranking according to compromise solution (MARCOS) [25], additive ratio assessment (ARAS) [72], and simple additive weighting (SAW) [73] models. During the evaluation of the performance rating of the automotive suppliers, the same criterion weights were used as in the SF-AHP weighting method. The results of the comparison analysis of methods are shown in Table 14. As can be seen in Figure 6, the correlation with other previous MCDM methods was very high. A similar ranking was calculated by all the comparison methods, confirming the result obtained by the proposed method in this study. Supplier CHE-05 (Vietnam National Chemical Group) always ranked as the optimal supplier. Supplier CHE-03 (South Basic Chemicals Joint Stock Company, District 1, Ho Chi Minh City, Vietnam) still ranked as the lowest performer. Through comparison with stable and mature MCDM ranking methods, we can see that the proposed MCDM model (SF-AHP and CoCoSo) is both applicable and rational. Therefore, the model's results are reliable and can offer a useful guideline for decision makers or policymakers in evaluating and selecting the optimal supplier in a sustainable automotive supply chain or in related industries.

Table 14. Results of the comparison analysis of methods.

Alternative	SF-AHP and COCOSO		SF-AHP and MABAC		SF-AHP and EDAS		SF-AHP and WASPAS		SF-AHP and MARCOS		SF-AHP and ARAS		SF-AHP and SAW	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
CHE-01	2.2495	4	−0.0901	4	0.3298	4	0.6520	4	0.5647	4	0.6402	4	0.6662	4
CHE-02	2.5454	3	0.0588	3	0.5805	2	0.7672	2	0.6619	2	0.7847	2	0.7809	2
CHE-03	1.3068	5	−0.1862	5	0.2126	5	0.6259	5	0.5435	5	0.6315	5	0.6412	5
CHE-04	2.9100	2	0.1046	2	0.5128	3	0.7189	3	0.6322	3	0.7113	3	0.7459	3
CHE-05	3.1039	1	0.3454	1	0.6334	1	0.7978	1	0.7202	1	0.8075	1	0.8497	1

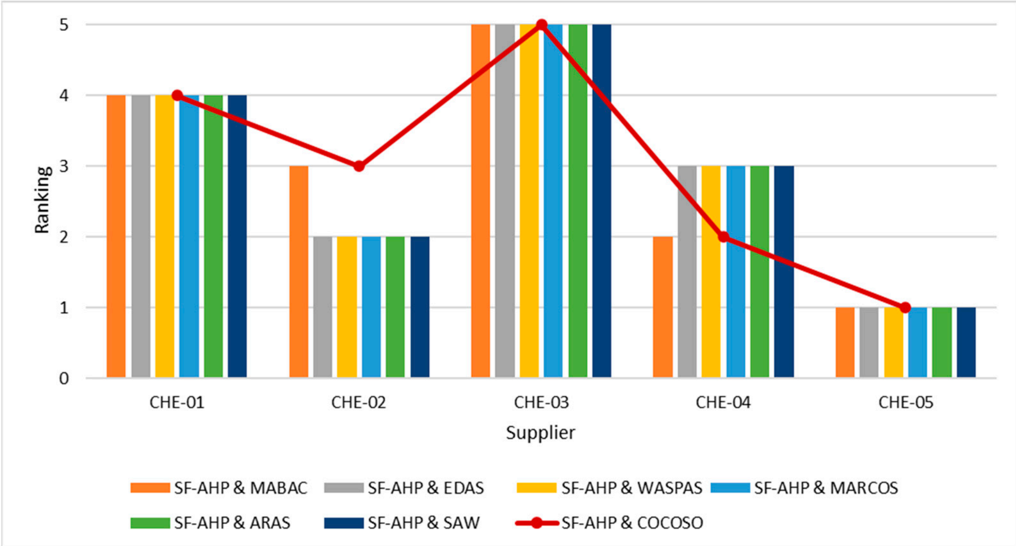

Figure 6. Comparison of the CoCoSo method with other MCDM methods.

6. Managerial Implications

A methodology for SSS with a focus on sustainable development was developed in the proposed case study in the Vietnamese chemical industry. Business owners and managers in the field could use the recommended framework to evaluate their suppliers in any type of supply chain. This study's findings emphasized the importance of TBL characteristics in SSS in the chemical sector. Finally, the findings showed that manufacturing enterprises must emphasize the integration of response mechanisms during SSS implementation, especially in today's world of global competition for long-term development and overall greater competitiveness. This will result in significant resource and cost savings, reduced environmental impacts, and a sustainable supply chain.

In this study, all the considered factors assist businesses in the chemical industry in dealing with various challenges and improving their efforts to develop environmentally friendly products, especially in the context of Vietnam. Developing SSS evaluation criteria based on industry experts' responses and the literature also represents a significant benefit of this work. Managers and practitioners can test the observation stability using the applied sensitivity analysis.

7. Conclusions

The adoption of sustainable practices has become a significant factor for corporate organizations in relation to their supply chains, as a result of greater awareness of environmental preservation and the resulting stringent laws. These variables can assist organizations to assess their long-term development and sustainability in the chemical sector, which is characterized by high risks, high pollution, and high efficiency. This paper establishes an effective SSS method with a focus on TBL features for the chemical industry from the perspective of an emerging country. After examining the literature and engaging industry experts, the assessment criteria system was created. The suggested method used SF-AHP to determine the weights of the assessment criteria and the novel CoCoSo method to subsequently rank the alternatives. To test the applicability of the proposed model, a case study was implemented in the Vietnamese chemical sector. From the SF-AHP findings, "equipment system and technology capability", "flexibility and reliability", "logistics cost", "green materials and technologies", and "on-time delivery" were the evaluation factors with the highest weights in the study. From the CoCoSo analysis, Vietnam National Chemical Group (CHE-05) was the best supplier among the alternatives, according to the final rating. To evaluate the model's resilience, a sensitivity analysis was performed, and the findings demonstrated that the applied approaches achieved common SSS rankings. This demonstrates that the proposed method is practical in nature.

The following are the key accomplishments and contributions of this study. First, this study is the first attempt to identify potential sustainable suppliers for businesses in the context of Vietnam, with a case study in the chemical industry, which has not previously been studied in the literature. A thorough set of criteria, including economic, social, and environmental sustainability features, was developed for analyzing the alternatives using a literature review and expert perspectives. This represents a key advantage of this study. In terms of approach, the combination of SF-AHP and CoCoSo was presented to address the SSS problem for the first time, and this was shown to be a relevant and effective technique for solving the SSS problem. All the assessment criteria and expert evaluations in this study could serve as a foundation enabling managers and decision makers in any type of organization to make educated judgments. Managers of enterprises could use our technique and the generated data to identify a suitable supplier for their firm, following the completion of the case study in Vietnam. This will result in major resource and expense savings, as well as a more effective response to the current crisis or any future crises. The model suggested can potentially be used in other industries and countries.

Although the methodology adopted in this study has been used successfully for prioritizing different alternatives and factors, it is not without some limitations. One limitation is the use of the AHP method. Although a consistency check was performed in the present study, the inconsistency in the pairwise comparison matrix should not be neglected. This inconsistency might occur in practice in other problems. The best–worst method (BWM) can overcome this drawback, as it reduces the burden on decision makers by requiring fewer pairwise comparisons. The analytic network process (ANP) method could also be a better option to avoid the interrelationships among factors. Hence, these methods are recommended for future studies. Another limitation is that the evaluation process depends on experts' involvement; thus, results are based on personal opinions, knowledge, and judgment. To avoid this limitation, 15 experts were utilized to provide different preferences. Thus, different multi-criteria evaluation techniques such as TOPSIS, VIKOR, PROMETHEE, COPRAS, and MULTIMOORA could be employed to achieve the same goal, and findings could be compared. In future research, by including unique and new criteria regarding coordination in the supply chain and criteria related to the present crisis (COVID-19), the suggested method in this study could also be used to handle dynamic and unpredictable environments. In addition, the present study could be applied to specific supply chain scenarios in different industries and countries, to assess whether the findings are generalizable.

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Appendix A

Table A1. The integrated SF-AHP comparison matrix.

	EC1			**EC2**			**EC3**			**EC4**			**EC5**		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0.5000	0.4000	0.4000	0.4796	0.5017	0.3177	0.3754	0.6163	0.2794	0.4978	0.4837	0.3140	0.3963	0.5919	0.2929
EC2	0.4585	0.5143	0.3245	0.5000	0.4000	0.4000	0.4774	0.5111	0.3068	0.4294	0.5529	0.3133	0.5174	0.4448	0.3393
EC3	0.5617	0.4149	0.3087	0.4621	0.5197	0.3404	0.5000	0.4000	0.4000	0.4845	0.4977	0.3138	0.5666	0.4243	0.2990
EC4	0.4378	0.5372	0.3171	0.5121	0.4554	0.4221	0.4498	0.5250	0.3175	0.5000	0.4000	0.4000	0.5173	0.4587	0.3286
EC5	0.5518	0.4219	0.3129	0.4185	0.5407	0.2720	0.4417	0.5234	0.3346	0.4289	0.5442	0.3240	0.5000	0.4000	0.4000
EC6	0.3537	0.6260	0.2893	0.4378	0.5372	0.1646	0.3734	0.6160	0.2821	0.4579	0.5034	0.3455	0.3470	0.6479	0.2618
EC7	0.5406	0.4321	0.3215	0.5069	0.4689	0.4338	0.5114	0.4569	0.3312	0.5728	0.3981	0.3082	0.3634	0.6301	0.2749
SO1	0.5839	0.3999	0.2920	0.5254	0.4503	0.4317	0.5816	0.3940	0.3079	0.4633	0.5105	0.3209	0.3836	0.5985	0.2960
SO2	0.4585	0.5067	0.3319	0.4585	0.5143	0.2471	0.3313	0.6645	0.2488	0.3497	0.6465	0.2550	0.3378	0.6488	0.2694
SO3	0.4457	0.5089	0.3517	0.4413	0.5490	0.0778	0.3497	0.6417	0.2623	0.4138	0.5743	0.2989	0.3734	0.6107	0.2892
SO4	0.3313	0.6668	0.2483	0.3836	0.6067	0.0409	0.2884	0.7121	0.2159	0.3164	0.6838	0.2350	0.3404	0.6546	0.2553
EN1	0.4417	0.5234	0.3346	0.4138	0.5617	0.2704	0.4463	0.5197	0.3313	0.4579	0.5111	0.3383	0.4289	0.5442	0.3240
EN2	0.4457	0.5165	0.3446	0.4579	0.5111	0.4319	0.4883	0.4844	0.3236	0.4663	0.4971	0.3359	0.3634	0.6198	0.2890
EN3	0.4711	0.5011	0.3249	0.5114	0.4569	0.4527	0.4503	0.5050	0.3486	0.4503	0.5050	0.3486	0.4674	0.4953	0.3388
EN4	0.3470	0.6479	0.2618	0.3982	0.5943	0.1501	0.2884	0.7065	0.2235	0.3164	0.6781	0.2426	0.3021	0.6964	0.2290
	EC6			**EC7**			**SO1**			**SO2**			**SO3**		
EC1	0.5889	0.3830	0.3120	0.4118	0.5748	0.3063	0.3657	0.6287	0.2663	0.4738	0.5017	0.3242	0.4946	0.4677	0.3488
EC2	0.4978	0.4837	0.3140	0.4431	0.5432	0.3139	0.4197	0.5689	0.3065	0.4796	0.5017	0.3177	0.5016	0.4936	0.2955
EC3	0.5821	0.4062	0.2986	0.4260	0.5579	0.3131	0.3489	0.6453	0.2717	0.6291	0.3667	0.2731	0.5995	0.3912	0.2859
EC4	0.4873	0.4825	0.3419	0.3784	0.6096	0.2861	0.4705	0.5128	0.3105	0.6069	0.3912	0.2770	0.5397	0.4514	0.3027
EC5	0.6171	0.3770	0.2816	0.6054	0.3870	0.2896	0.5700	0.4099	0.3088	0.6077	0.3730	0.2966	0.5751	0.4062	0.3066
EC6	0.5000	0.4000	0.4000	0.4497	0.5312	0.3206	0.4346	0.5529	0.3070	0.5642	0.4153	0.3134	0.5584	0.4205	0.3178
EC7	0.4934	0.4751	0.3325	0.5000	0.4000	0.4000	0.5574	0.4153	0.3209	0.6160	0.3709	0.2851	0.5708	0.3928	0.3263
SO1	0.5121	0.4644	0.3212	0.3910	0.5843	0.3096	0.5000	0.4000	0.4000	0.5642	0.4153	0.3134	0.5369	0.4435	0.3112
SO2	0.3910	0.5902	0.3026	0.3404	0.6499	0.2624	0.3910	0.5902	0.3026	0.5000	0.4000	0.4000	0.4193	0.5729	0.2893
SO3	0.3986	0.5818	0.3092	0.3705	0.6012	0.3092	0.3951	0.5842	0.2997	0.5121	0.4696	0.3077	0.5000	0.4000	0.4000
SO4	0.3565	0.6347	0.2689	0.2997	0.6896	0.2495	0.3734	0.6135	0.2886	0.3079	0.6908	0.2354	0.3565	0.6272	0.2825
EN1	0.4372	0.5342	0.3308	0.3986	0.5757	0.3162	0.4417	0.5234	0.3346	0.4934	0.4751	0.3325	0.5891	0.3846	0.2987
EN2	0.5069	0.4689	0.3251	0.3565	0.6347	0.2689	0.6115	0.3700	0.2833	0.6638	0.3312	0.2494	0.5174	0.4507	0.3252
EN3	0.4407	0.5322	0.3246	0.4579	0.5111	0.3383	0.5081	0.4633	0.3231	0.5406	0.4321	0.3215	0.5121	0.4554	0.3291
EN4	0.2940	0.6992	0.2364	0.3634	0.6275	0.2755	0.3672	0.6249	0.2717	0.3634	0.6275	0.2755	0.3139	0.6808	0.2488
	SO4			**EN1**			**EN2**			**EN3**			**EN4**		
EC1	0.6484	0.3490	0.2650	0.4962	0.4758	0.3318	0.5006	0.4677	0.3425	0.4668	0.5149	0.3174	0.6171	0.3770	0.2816
EC2	0.5666	0.4243	0.2990	0.5267	0.4514	0.3174	0.4932	0.4825	0.3356	0.4260	0.5579	0.3131	0.5410	0.4548	0.2916
EC3	0.6791	0.3228	0.2443	0.4868	0.4879	0.3246	0.4422	0.5430	0.3099	0.4852	0.4801	0.3417	0.6509	0.3422	0.2640
EC4	0.6226	0.3811	0.2708	0.4932	0.4825	0.3356	0.4701	0.5039	0.3308	0.4852	0.4801	0.3417	0.6530	0.3375	0.2657
EC5	0.6235	0.3709	0.2759	0.5173	0.4587	0.3286	0.5909	0.3870	0.3063	0.4689	0.5056	0.3278	0.6463	0.3535	0.2634
EC6	0.5934	0.3969	0.2912	0.5120	0.4632	0.3324	0.4431	0.5432	0.3139	0.5035	0.4739	0.3283	0.6560	0.3301	0.2718
EC7	0.6414	0.3372	0.2872	0.5517	0.4205	0.3251	0.5934	0.3969	0.2912	0.4932	0.4825	0.3356	0.5873	0.4026	0.2962
SO1	0.5928	0.3909	0.3005	0.4962	0.4758	0.3318	0.3399	0.6546	0.2533	0.4212	0.5653	0.2998	0.5762	0.4179	0.2881
SO2	0.6397	0.3600	0.2695	0.4497	0.5312	0.3206	0.2837	0.7164	0.2081	0.4118	0.5748	0.3063	0.5873	0.4026	0.2962
SO3	0.5970	0.3811	0.3014	0.3517	0.6396	0.2662	0.4212	0.5622	0.3065	0.4294	0.5529	0.3133	0.6255	0.3664	0.2846
SO4	0.5000	0.4000	0.4000	0.4008	0.5880	0.2994	0.3613	0.6287	0.2728	0.3857	0.6044	0.2861	0.6291	0.3667	0.2731
EN1	0.5454	0.4288	0.3196	0.5000	0.4000	0.4000	0.4902	0.4758	0.3382	0.5981	0.3870	0.2981	0.6807	0.3281	0.2281
EN2	0.5839	0.3885	0.3011	0.4417	0.5160	0.3418	0.5000	0.4000	0.4000	0.5305	0.4378	0.3319	0.6725	0.3182	0.2492
EN3	0.5567	0.4184	0.3108	0.3634	0.6250	0.2820	0.4095	0.5585	0.3238	0.5000	0.4000	0.4000	0.5598	0.4243	0.3069
EN4	0.3313	0.6645	0.2488	0.2776	0.7240	0.1957	0.2964	0.6986	0.2233	0.3836	0.6012	0.2894	0.5000	0.4000	0.4000

Table A2. The weighted comparability sequence matrix of the CoCoSo model.

Weights of Criteria	**0.0684**	**0.0666**	**0.0751**	**0.0709**	**0.0768**	**0.0678**	**0.0753**	**0.0694**	**0.0602**	**0.0621**	**0.0532**	**0.0691**	**0.0718**	**0.0658**	**0.0475**
Types of criteria	Benefit	Cost	Cost	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit
Criteria	EC1	EC2	EC3	EC4	EC5	EC6	EC7	SO1	SO2	SO3	SO4	EN1	EN2	EN3	EN4
CHE-01	0.0282	0.0328	0.0424	0.0404	0.0241	0.0411	0.0392	0.0278	0.0252	0.0222	0.0097	0.0111	0.0000	0.0000	0.0000
CHE-02	0.0000	0.0666	0.0751	0.0600	0.0576	0.0377	0.0323	0.0198	0.0267	0.0310	0.0000	0.0000	0.0575	0.0219	0.0069
CHE-03	0.0000	0.0545	0.0711	0.0000	0.0000	0.0678	0.0000	0.0000	0.0000	0.0000	0.0152	0.0384	0.0000	0.0000	0.0012
CHE-04	0.0403	0.0272	0.0277	0.0491	0.0576	0.0151	0.0753	0.0595	0.0602	0.0388	0.0228	0.0077	0.0000	0.0219	0.0359
CHE-05	0.0684	0.0000	0.0000	0.0709	0.0768	0.0000	0.0646	0.0694	0.0602	0.0621	0.0532	0.0691	0.0718	0.0658	0.0475

Table A3. The exponentially weighted comparability sequence matrix of the CoCoSo model.

Weights of Criteria	**0.0684**	**0.0666**	**0.0751**	**0.0709**	**0.0768**	**0.0678**	**0.0753**	**0.0694**	**0.0602**	**0.0621**	**0.0532**	**0.0691**	**0.0718**	**0.0658**	**0.0475**
Types of criteria	Benefit	Cost	Cost	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit	Benefit
Criteria	EC1	EC2	EC3	EC4	EC5	EC6	EC7	SO1	SO2	SO3	SO4	EN1	EN2	EN3	EN4
CHE-01	0.9412	0.9540	0.9580	0.9608	0.9148	0.9667	0.9520	0.9384	0.9490	0.9383	0.9136	0.8814	0.0000	0.0000	0.0000
CHE-02	0.0000	1.0000	1.0000	0.9882	0.9782	0.9609	0.9382	0.9167	0.9524	0.9579	0.0000	0.0000	0.9841	0.9303	0.9128
CHE-03	0.0790	0.9867	0.9959	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.9355	0.9602	0.0799	0.0977	0.8384
CHE-04	0.9643	0.9422	0.9278	0.9742	0.9782	0.9031	1.0000	0.9894	1.0000	0.9712	0.9559	0.8591	0.0799	0.9303	0.9868
CHE-05	1.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.9885	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

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